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NAVAL POSTGRADUATE SCHOOL

Monterey, California

GENERAL PROBLEM SOLVING:

NAVY REQUIREMENTS AND SOLUTIONS

by

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and

Kathleen Knott

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This survey has found a growing interest in the area of problem solving. This interest began with work in cognitive psychology and artificial intelligence in the 1950's and gradually spread to influence education and management. There is little evidence in the literature to indicate that teaching generic problem solving produces improvement in problem solving abilities. One factor complicating this is the lack of adequate definitions of problem solving skills and the lack of test instruments to measure these skills. Some authors suggest that generic problem solving skills

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GENERAL PROBLEM SOLVING:
NAVY REQUIREMENTS AND SOLUTIONS

by

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and
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SUMMARY

Problem

In assigning officers to jobs, the Navy has a general management philosophy. An officer is expected to handle any management situation. General skills are regarded as more important than specialized training. This can mean that an officer may have several months of unproductive learning time before mastering the skills needed for a new assignment. If officers could be given a set of useful general problem solving skills, it is possible that this learning time could be shortened.

Objective

This research is a preliminary study with two major objectives. The first is to perform a literature survey of the problem solving and artificial intelligence literature relevant to Navy needs. The second objective is to investigate approaches to problem solving that could be taught to Naval officers for use in their jobs.

Approach

This preliminary study is a literature survey and problem structuring effort. The study of problem solving is spread across many disciplines, and the first step is to investigate this literature.

Results and Conclusions

This survey has found a growing interest in the area of problem solving. This interest began with work in cognitive psychology and artificial intelligence in the 1950's and gradually spread to influence education and management. There is little evidence in the literature to indicate that teaching generic problem solving produces improvement in problem solving abilities. One factor complicating this is the lack of adequate definitions of problem solving skills and the lack of test instruments to measure these skills. Some authors suggest that generic problem solving skills are best taught in the context more conventional courses. The work in teaching generic problem solving is still largely exploratory and unvalidated.

Future Research Considerations

There is a need for both theoretical and applied research in problem solving. Topics of interest include:

1. Design of measures of problem solving skills.

2. Design of course modules in problem solving covering both domain specific and general skills.

3. Experiments where the usefulness of teaching problem solving skills is tested.

4. Studies of computers and human problem solving. These should focus on the computer as a problem environment and ways in which the computer can aid human problem solving.

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INTRODUCTION

A long standing issue in problem solving is whether general problem solving techniques offer a useful alternative to domain specific problem solving techniques. Early researchers in cognitive psychology and artificial intelligence concentrated on general problem solving [Feigenbaum and Feldman, 1963; Newell and Simon, 1972]. More recent work has dealt with knowledge based systems and expert systems which use these general techniques but apply them to specific problem domains [Barr and Feigenbaum, 1981; Barr and Feigenbaum, 1982; Cohen and Feigenbaum, 1982]. After thirty years of research, the issues are still far from being resolved.

If generic problem solving skills can be successfully taught, this could be valuable in the education of Naval officers. Due to frequent personnel rotation, Navy officers are asked to solve problems and make decisions in areas where they have little initial knowledge of the subject matter. A useful set of generic problem solving skills could be of great benefit to the Navy and individual officers. These skills could be used to reduce the time required to get an officer up to speed in a new assignment. The idea of teaching generic problem solving skills is not new. Courses are in place at several universities, and there is a growing literature [Rubenstein, 1980; Hayes, 1981]. This work still must be regarded as preliminary, however.

The objective of this study is to better understand problem classes and related solution strategies. To bound the requirement, we will focus on the question of problem analysis instead of on specific problem solving skills in any domain. The most important step in any type of problem solving is to recognize and classify the problem. Only then can an individual bring specific problem solving techniques to bear.

The approach taken will be to survey the literature in problem solving, to develop a model of the problem solving process and to identify candidates for teaching and future research. In most courses, solution strategies are cognitively tied to the context in which they were learned. This can cause their applicability to other domains to be overlooked. Thus, the aim of any instruction in generic problem solving is to get the problem solver to see solution techniques as general methods that can be used in a variety of contexts. The hope is that a person who knows how to remove skills from a context will be a more successful problem solver in a variety of domains.

One item of interest for follow on work is the extent to which different modes of computer access can be helpful in structuring and solving problems. Computers have great potential in aiding human problem solving. Some of the earliest work in artificial intelligence grew out of attempts by cognitive psychologists to simulate human problem solving processes on computers. This work led to increased understanding of both humans and computers.

1.1 PROBLEM SOLVING AND NAVY CAREER PATTERNS

A typical Naval officer's career is likely to involve many different jobs and types of responsibility. The Navy is not a single monolithic entity but is divided into many different communities and warfare specialties. Examples would include such areas as supply, surface warfare, anti-submarine warfare, submarines, aviation and so on. An officer's career begins in a particular community. Even within a community, there is wide variation in jobs. An officer may start in operational jobs and then move on to supervisory (e.g. department head) and managerial jobs (e.g. executive officer). At higher levels in the Navy, an officer may be transferred from the community. This kind of shift requires that abandoning the narrower perspective of the community and warfare specialty and instead viewing things from a Navy-wide perspective.

1.2 THE STUDY OF GENERAL PROBLEM SOLVING

Considering that human beings have been problem solvers for all their existence, the actual study of problem solving has a short history. Problem solving has been viewed as an art. You were either good at it or you were not. Little effort was made (or is being made) to teach problem solving as such. Most teaching is directed at domain specific skills. Examples of successful solution strategies are presented, and students are expected to emulate these strategies.

An exception to this approach was Georg Polya's *How to Solve It*, a classic book of solution strategies for mathematical problems. Polya laid out the problem solving process as a series of steps. These are given in Figure 1. Polya's book offered many helpful examples for using this approach. The methods he used were actually quite general, but the domain was limited to mathematics.

1. Understand the problem.
   What is the unknown? What are the data? What is the condition? Draw a figure.
   Introduce suitable notation. Separate various parts of the condition.

2. Devise a Plan.
   Have you seen the same problem before? Do you know a related problem? Consider auxiliary problems.
   Go back to definitions.

3. Carry out Your Solution Plan.
   Check each step. Make sure each step is correct.

4. Evaluate your solution.
   Can you check the result? Can you derive the result differently? Can you use the result or the method for some other problem?

Figure 1: Polya's Problem Solving Methodology

In the 1950's, computers made it possible to test out theories of problem solving. Allen Newell and Herbert Simon began to develop theories of human problem solving. Their view was that a good theory of problem solving should also be a good problem solver. They used computer simulation to test their theories. This work was very productive. It led to advances in psychology, education and computer science. They worked on many problem solving programs including a logic theorist, a chess program and even a general problem solving program. This was nearly thirty years ago, and we are still working out the implications of this work.

1.3 TEACHING GENERAL PROBLEM SOLVING

There has been an increasing interest in incorporating courses in problem solving into curricula. General problem solving courses are taught to undergraduates in the Department of Psychology at Carnegie-Mellon University and in the College of Engineering at UCLA [Hayes, 1981; Rubenstein, 1980]. These courses encourage students to see their skills in a general context and to learn how to learn. These courses have been in place for several years. The results have been good enough to continue them, however, there has been no formal validation of these courses.

The interest in general problem solving can also be found in the educational psychology literature [Baird, 1983; Bourne, 1970; Feldhusen, et. al., 1972, 1975, 1979, 1980; Genya, 1983; Houtz et. al., 1973; Karat, 1982; Lukas, et. al., 1971; Pitt, 1983; Post and Brennan, 1976; Reif and Heller, 1982; Schwieger, 1974; Speedie, et. al., 1973; Thorson, 1977 and Tuma and Reif, 1980]. Most of these papers deal with experiments in teaching problem solving. There is little in the way of formal validation in the papers. This is not surprising since there is no generally accepted measure of problem solving ability although we were surprised to find that there are some attempts to measure this ability. One such test instrument is the Purdue Elementary Problem Solving Inventory [Purdue, 1973]. This test is aimed at elementary school students of different socioeconomic backgrounds. It is only partially relevant to this study.

There are many questions about the teaching of problem solving. These would include:

1. What is general problem solving?

2. How is problem solving ability measured?

3. Is the course effective in improving problem solving ability using some measure?

These questions are not answered by any of the literature we have found, although people are starting to pose them in one way or another. The teaching of problem solving skills would best be described as interesting but unvalidated.

1.4 STRUCTURES OF PROBLEMS

One major difficulty is that we do not see "general" problems. All problems we are presented with are domain specific. We spend most our school years from kindergarten through graduate school learning problem solving techniques for particular areas. It becomes difficult to see the forest for the trees. There are several ways that the structuring of problems can be approached. One way was the technique used early in the history of artificial intelligence. This was to assume that there were general techniques for solving problems and then try to design intelligent programs that incorporated these techniques and turn them loose on a variety of domains. The best example of this approach is the General Problem Solver (GPS) of Newell, Shaw and Simon [Ernst and Newell, 1969]. This was not really a unified computer program but instead was a loose alliance of concepts and programs that tried to achieve general problem solving ability in a variety of domains.

In more recent years, this approach has changed. Artificial intelligence has moved in the direction of knowledge based systems and expert problem solvers which operate in limited domains (actually, GPS operated in limited domains as well, but its ambitions were much broader). There are many examples of expert or knowledge based systems. Two such systems are MYCIN which does infectious disease diagnosis and PROSPECTOR which aids in the discovery of mineral deposits [Barr and Feigenbaum, 1981]. The domain specific problem solvers do not represent a rejection of the earlier general problem solvers. They build on the earlier work using the same heuristics for analyzing problems. They extend it by using more sophisticated methods for structuring knowledge and more special purpose heuristics.

The most important thing is to develop a model of the problem solving process and then try to decide what pieces of the model should be taught. One such model might be:

1. Choose a problem.

2. Choose a representation for the problem.

3. Choose a solution method for your problem and representation.

4. Evaluate the solution method at each point.

5. Evaluate the result and recycle if necessary.

Various approaches to problem solving will concentrate on one or another of these steps. Traditional courses typically focus on the last two points. The problem and the representation are already chosen for you. What matters is applying the solution method (e.g. the one in the book) and evaluating it (getting the "right" answer). This can be unfortunate since it obstructs one's ability to generalize to different problem domains. This would seem to be the case in the "real" world. There are numerous papers that document the lack of transfer effects in problem solving [e.g. Sweller, 1980].

There seems to be ample evidence that much can be gained by concentrating on the first two points of this model, namely the issues of problem finding and representation. Often, a problem can be solved by recasting it in different terms. As an example, in the Middle Ages, it was believed that by diligent study, a university student should be able to master the art of long division, something that is normally taught in the third or fourth grade now. The problem was not that the medievals were any less intelligent than we are - they weren't. They just had to cope with long division using Roman numerals. Changing the representation of the problem caused the problem to disappear.

One can find many similar examples. If you go into a mathematics library that dates back into the nineteenth century, you will find many large volumes of algebra books that deal with the theory of determinants. These books detail all the tricks for dealing with determinants that we learned in Algebra I many more besides. All that is gone today. The work is still as valid as it ever was. The advent of digital computers has simply made the use of tricks with determinants unnecessary for solving large systems of equations.

One approach that has been taken lately in the teaching of problem solving is to concentrate on developing problem finding and representation skills. The theory seems to be that these skills are left undeveloped by conventional teaching techniques or even that these skills are discouraged. This is the approach taken by Edward DeBono in his creativity courses. DeBono uses a variety of techniques to encourage subjects to try new approaches to problems. He tries to discourage what he calls "vertical thinking" by which he seems to mean rigidly structured linear approaches to problem solving. He offers what he calls "lateral thinking" as an alternative. By this, he means the use of techniques which try to search out alternatives early in the problem solving process. His techniques rely heavily on brainstorming. In some ways, they seem to resemble Dada, the modern art movement of the 1920's espoused by Salvador Dali. One aim of Dada was to encourage a greater sensitivity to beauty by presenting images that were deliberately shocking. In the same way, DeBono suggests posing "silly" solutions to problems to help break out of preconceived notions of what is right.

DeBono's work is widely touted to executives and seems to achieve a certain degree of success. Academics are less excited about it, no doubt partly because of DeBono's style. He does not give credit to others for portions of his work which is derivative. The book is written in a generally pompous and authoritative tone. His approaches to problem finding and structuring are probably worth considering. They are far from a complete approach to problem solving. But, they do offer guidance in the initial stages of problem solving where people seem to need some encouragement.

Another way to view problem solving is as a set of different domains that are best handled by specialists. If the problem solver is a manager, then his function should be to know enough about the different domains to be able to call in the proper expert. This was the approach taken in a paper written for the Naval Personnel Research and Development Center [Doherty, et. al., 1980]. This is similar to the approach taken by many MBA programs. The manager is viewed as a generalist whose function is to lead, to motivate, and to know when to call in the experts. The educational process makes the students familiar with the different areas in a business so that they could call for specialists when necessary.

The paper above had certain flaws. The authors seem to come from an organizational theory or organizational design background. Their taxonomy of problems and solutions was highly detailed in these areas. Other areas of management that are equally complex received one phrase dismissals (operations research or management information systems). Mark Twain's comment about everything looking like a nail to a man who only has a hammer seems appropriate here. But even if their taxonomy had been expanded, problems would remain. Problem taxonomies completely ignore issues of problem finding and choice of representation. Before one can call in the experts, one must decide that something is a problem. The problem must be represented in a certain way. By the time one calls in the experts, much of the important problem solving work has been done.

If one had to lay out the skills for problem solvers, the choices would have to go beyond a simple taxonomy. Choices would include:

1. Understanding skills.
   A good problem solver must be able to look at a situation in many different ways. Such a person must have a rich variety of representations for problems and know how to apply them in many different problem domains.

2. Problem finding skills.
   It might seem that problem finding is unnecessary since problems are usually thought of as forcing themselves on our attention. Actually, one issue is what we should consider the problem to be in a given situation. This relates to the previous point of choice of representation.

3. Problem structuring skills.
   Once confronted with a problem, a problem solver must be able to structure the problem in such a way that it can be solved.

4. Analytic skills.
   These are the heuristics and other methods for solving problems that the cognitive psychologists and artificial intelligence researchers study.

5. Knowledge base.
   To be able to solve problems, a person should have a base of knowledge in the problem domain under consideration. This knowledge should be structured so that it is accessible and can be used in the solution process.

The important point in understanding and teaching problem solving is to develop an overall model of the process, to teach problem solving as a process that can be decomposed into parts, to teach the process of decomposition, and to teach each of the parts of the process. This requires much understanding and practice from both students and teachers. It is not clear if it has ever really been tried. Most of us think that we are teaching "problem solving" whatever our specialty may be. In fact, most of us are experts in one domain or another, and we do not bring a great deal of true generality to the process. This is the challenge in teaching general problem solving. Whether it can be carried out successfully is an unproved proposition.

2

JOB REQUIREMENTS FOR NAVAL OFFICERS

2.1 NAVAL ORGANIZATION

The Navy is organized into operating forces and supporting shore activities. The operating forces are comprised of ships, aircraft, and Marine combat units, which have combat and seagoing readiness requirements whether they are based ashore or at sea [Price, 1973]. The primary function of shore activities is to supply, maintain and support the Navy's operating forces by obtaining material, services and personnel.' The career Naval officer, who achieves the higher ranks, will command both operating and shore activities. The next section describes the career pattern of a Naval officer. It is important to note that the Naval officer has dual responsibilities. The officer is trained an operational job (e.g. fighter pilot or Weapons Officer) and at the same time must be a general manager, tending to the administrative needs of the operating forces.

2.2 NAVAL OFFICER CAREER DEVELOPMENT

The general career pattern for the Naval officer varies with the type of officer. Under the U. S. Code, Title 110, all officer classifications and their billets correspond to a four digit designator code. Seven major officer categories can be identified[1]. They are:

1. Undesignated Officers, designator 1100

2. Surface Warfare Officers, designator 1110

3. Submarine Warfare Officers, designator 1120

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[1] Shepherd, *Career Planning Information in Officer Professional Development*, 1974, p.13.

4. Special Warfare Officers, designator 1130

5. Aviation Warfare Officers, designator 1300

6. Restricted Line and Special Duty Officers, designator - various

7. Staff Corps Officers, designator - various

Within each of the warfare categories (designator groupings) are job specializations, which are distinguished by the last two digits of the designator code (e.g. Pilot (1310), Flight Officer (1320)). Officers in a warfare specialty will further subspecialize into non-warfare areas. Each of the subspecialty areas receives an additional designator code listed under the Navy Officer Codes System.

The Naval officer's career evolves through a progression of duty and training assignments. The career pattern is to some extent fixed once the newly commissioned officer commits to a particular specialization within a designator. The career patterns of Unrestricted Line Officers in surface, aviation and submarine communities are established by following the prescribed series of sea or squadron and shore billets appropriate for success within each community. The first duty is typically operational. The junior line officer is assigned a sea or squadron tour which involves extensive training and experience in the warfare specialty. The goal here is to develop the officer's knowledge of the sea or squadron operations, equipment and warfare tactics. Emphasis is placed on performing those duties that lead to the largest gain in knowledge and on-the-job training in the specialty. Assignments to various duties are selected to build and reinforce the officer's operational experience in a particular warfare specialty. Duty assignments are also diversified with the expressed intent to cross train the officer to become proficient and knowledgeable across the spectrum of naval operations. A major goal of an officer is to obtain the command billets of Executive and finally Commanding Officer of a ship or squadron.

The shore duty assignments generally remain operationally oriented but are more varied and open to be tailored to the officer's particular specialty interests. Shore tours are designed to enhance the value of the officer to the Navy and train the officer to function at higher levels within its organizational structure. The officer receives either additional formal training ashore or is assigned a special staff position. For the first shore tour of duty, the officer will choose a subspecialty which will determine, for the most part, future assignments ashore. Some of the possibilities for shore tours include postgraduate education, service college, staff duty, training instructor, or recruiting assignment.

As an officer's career progresses through the assignments of sea or squadron and shore tour, those achieving higher ranks eventually assume a major shore or staff command. The job of the Commanding Officer is to manage Naval support and operational forces. Major commands involve the senior Naval officer in the management of activities not particularly related to their warfare specialty.

A guidebook on Navy careers [Naval Military Personnel Command, 1979] provides a general outline of for the several officer types. The typical career patterns for the Surface Warfare, Aviation, and the Nuclear Surface Warfare Officers are illustrated in Figures 2, 3, 4, and 5 of this report. The major steps of a line officer's career pattern were summarized in a Master's thesis at the Naval Postgraduate School as follows:

a. Major shore command assignment on or about the 22-year mark;

b. Generally, over 50% of time in service will be afloat or squadron units or in training for those units (for officers in paths shown in Figures 2, 3, 4, and 5);

c. The likelihood of Washington shore assignment for senior officers (O-4 and above); and

d. The predominance of subspecialty and staff duty for shore duty assignments[2].

For the Restricted and Staff Officers, the career patterns are much more specific to their designator. However, as with the Unrestricted Line communities, these officer also rotate through assignments relevant to their specialty and management support positions.

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[2] James V. Hodges and B. Rosakranse, *Analysis of Training for Prospective Commanding Officers of Major Shore Activities*, 1981, p. 38.

SURFACE WARFARE OFFICER PROFESSIONAL DEVELOPMENT PATH

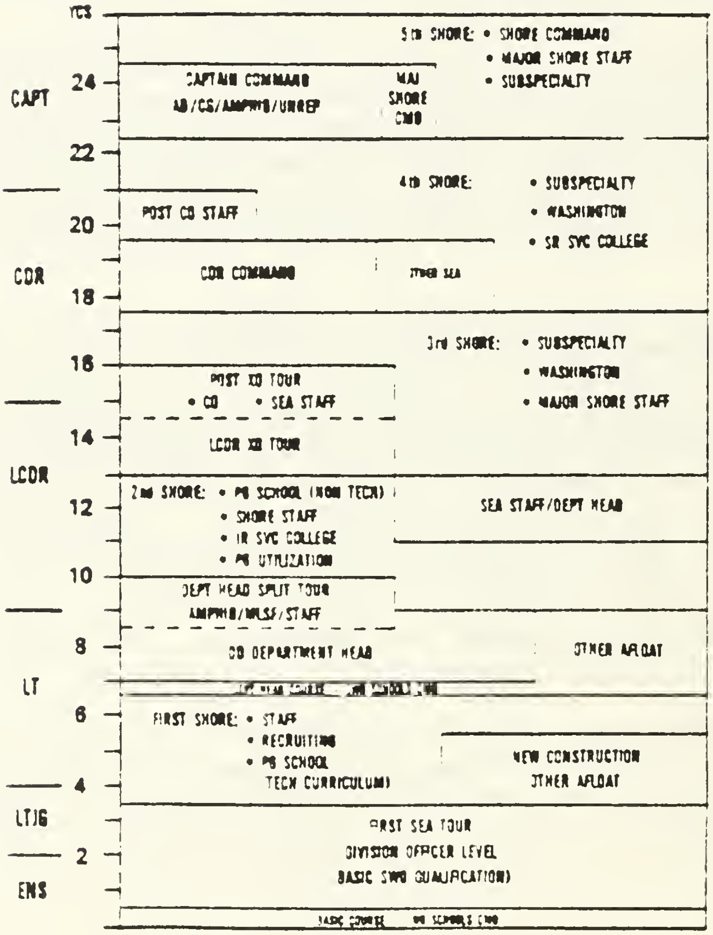

Figure 2: Surface Warfare Officer Professional Development Path

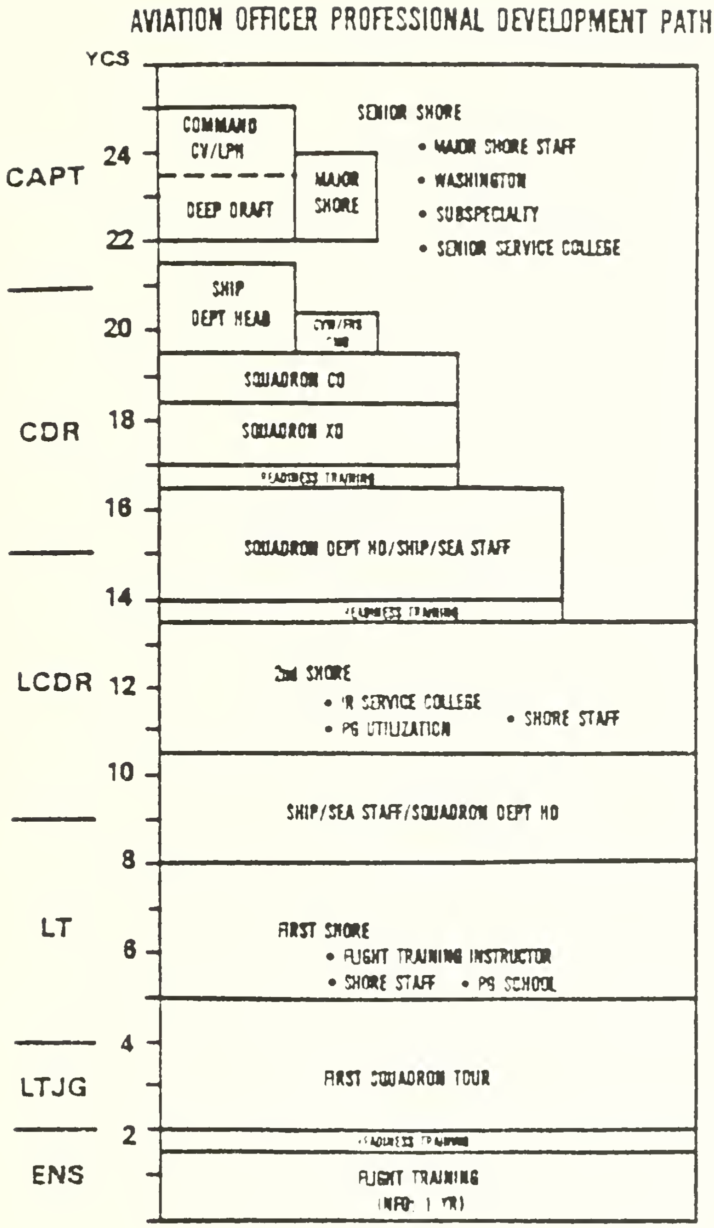

Figure 3: Aviation Officer Professional Development Path

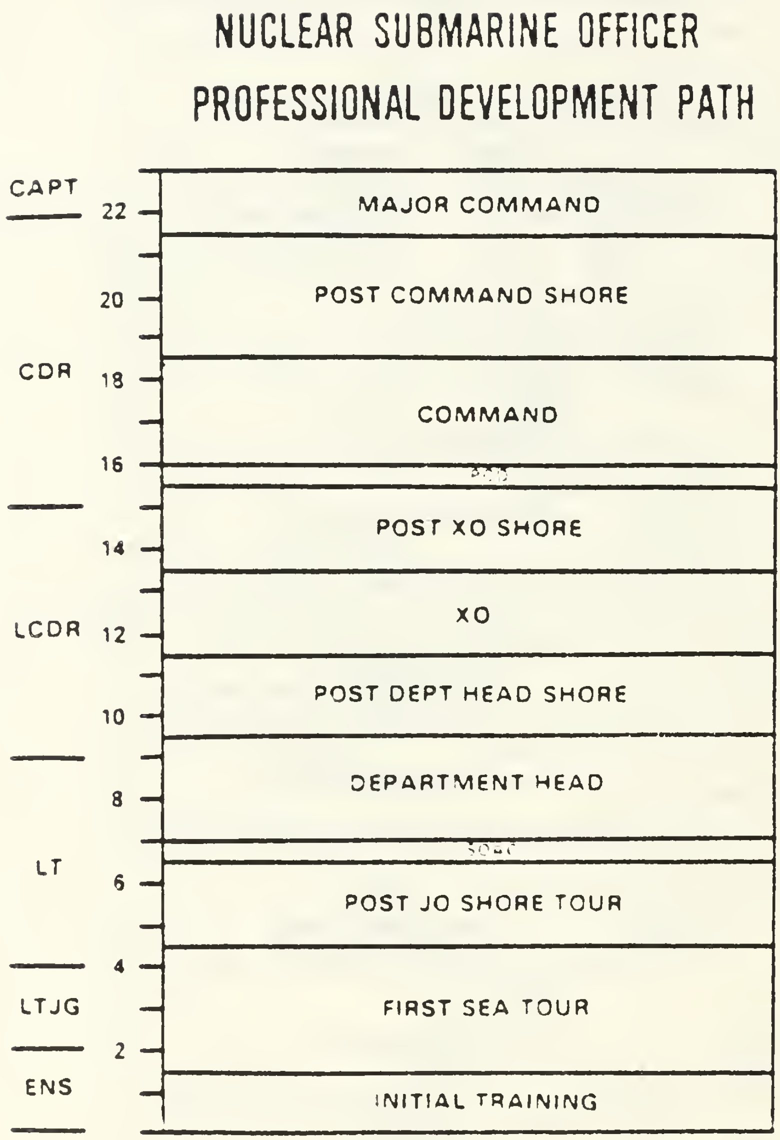

Figure 4: Nuclear Submarine Officer Professional Development Path

NUCLEAR SURFACE WARFARE OFFICER PROFESSIONAL DEVELOPMENT PATH

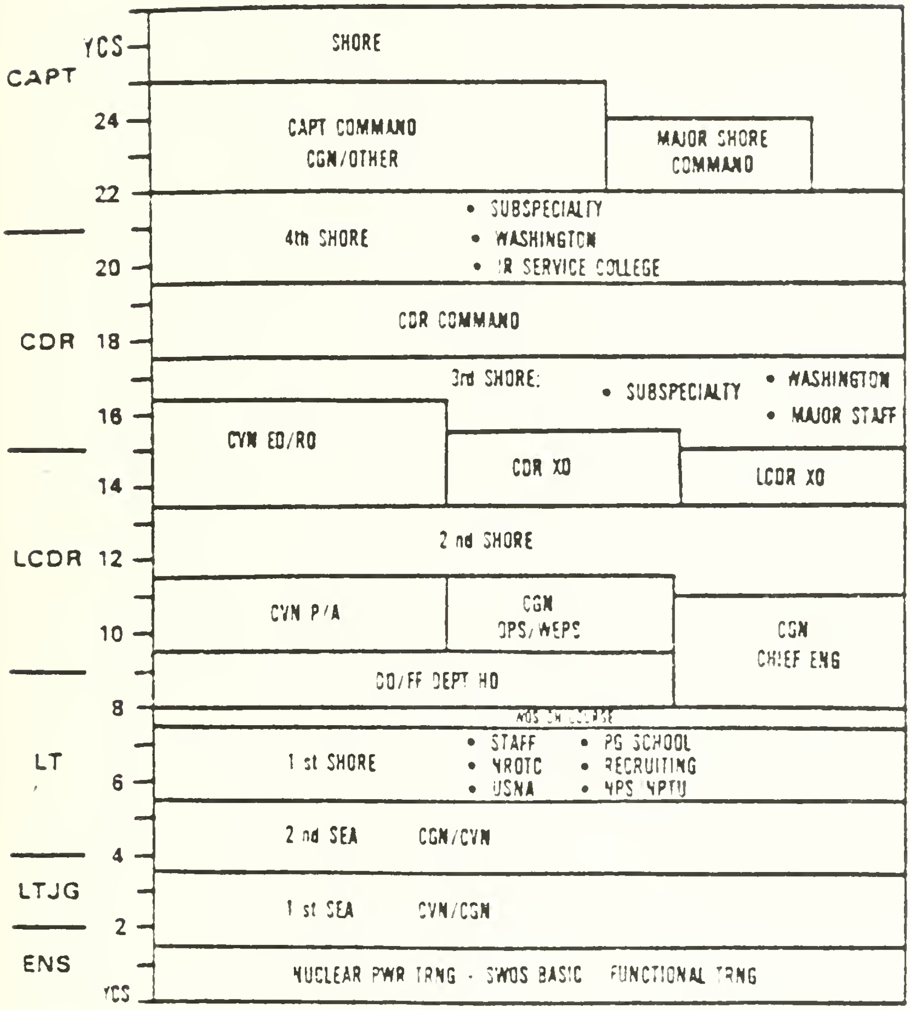

Figure 5: Nuclear Surface Officer Professional Development Path

2.3 THE OFFICER AS GENERAL MANAGER

The normal career path for a Naval officer includes assignment as a department head, executive and commanding officer, and ultimately a major shore command. Although an officer receives the extensive technical training within a warfare specialization, only a relatively short period of time is spent functioning in this specialty. Officers rotate every two or three years between their military specialty and managerial support positions. As an officer's career progresses, increasing amounts of time are devoted to management functions.

2.4 MANAGEMENT TRAINING PROGRAMS

To date, the only formal training a Naval officer receives to develop managerial skills is the Leadership and Management Education and Training (LMET) program, which is offered to officers of any rank, and two other courses for incumbent senior officers of major shore command billets, through the Naval Civilian Personnel Command [Hodges, 1981; Vandover, 1981].

2.4.1 Leadership and Management Education and Training

The LMET training program was developed by McBer and Company based on McClelland's theoretical concepts and research on leadership and achievement. The program was formally implemented in 1978 and currently has five levels of managerial training. The levels of training differ mainly in the content and the context corresponding to the type of managerial setting encountered under the position as commanding officer or executive officer, department head, division officer, chief petty officer or petty officer. The instruction period is 10 working days. On the east coast, the LMET is offered in Memphis, Tennessee; Little Creek, Virginia; New London, Connecticut; Mayport, Florida; Pensacola, Florida; Newport, Rhode Island; Charleston, South Carolina. On the west coast, the LMET course is offered in Coronado, California; San Diego, California; Bangor, Washington; Treasure Island, California; and Pearl Harbor. Officers typically have the opportunity to receive the LMET training enroute to their new duty stations.

2.4.2 Training through the Naval Civilian Personnel Command

The Naval Civilian Personnel Command offers two courses to senior Naval officers. They are the Senior Line Management Institute (5 day course), and the Prospective Commanding Officer Shore Station Management Training Program (three week course). The former course emphasizes civilian personnel issues and the latter focuses on the management issues involving a typical shore command.

2.5 PROBLEMS ENCOUNTERED DURING A NAVAL OFFICER'S CAREER

Problems associated with officer management effectiveness have been observed [Rezin, 1976]. The managerial problems are perceived to be due to the lack of formal managerial training, short tours of duty, and short Naval careers [Shepherd, 1974, Rezin, 1976; Vandover, 1981]. However, the conventional principles of management as they apply to the private sector or governmental agencies do not strictly apply to the Naval officer performing administrative and management duties. The fact still remains that the Navy is a military organization and the nature of an "officer's job" is defined within its structure. That is, the officer is skilled within a warfare specialty or specialization and at the same time functions as a general manager. In the private sector and other governmental agencies people usually function in the single role of manager. In general, Naval officers are technically prepared to solve problems encountered in their specialties. Managerial skills, however, must be learned informally from the administrative responsibilities associated with duty assignments.

3

A MODEL OF THE PROBLEM SOLVING PROCESS

Before one can teach problem solving, one must have a definition of a problem. A good choice is:

> A person is confronted with a problem when he wants something and does not know immediately what series of actions he can perform to get it.[3]

The problem may be of any type, mathematical, social, managerial or whatever. The main feature is dissonance between the initial state and the goal state. Presumably the problem solver has some means to translate the initial state to the goal state, although the transformations to be used may not always be obvious.

Next, one must have a model of the problem solving process. There are many ways to do this. We will use the model shown in Figure 6 based on that of Newell and Simon to represent the process. This is a general model of a solution process. It is similar to the design process in systems analysis and software engineering. This should be no surprise since these disciplines are simply formal, structured problem solving methodologies. It should be recognized that this process is not a rigid, linear march toward a solution. At any point in the process, it is possible to backtrack and try another approach. Novice problem solvers frequently fail to realize this when they try to solve problems. Giving up too soon is one thing which distinguishes poor problem solvers from good ones.

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[3] Newell and Simon, *Human Problem Solving*, p. 72.

1. Choose a representation for the problem.

2. Choose a method for solving the problem from the collection of methods that work on the representation chosen.

3. During the application of the method, several things can happen. They include:

   a) The problem is solved.

   b) The method is inadequate, and another method must be chosen.

   c) The representation is inadequate, and another representation must be chosen.

   d) The attempt to solve the problem is partially successful and a new subproblem is generated.

   e) The attempt to solve the problem is abandoned.

4. During the solution attempt, subgoals are likely to be generated. These can be put aside for later work applying the same general problem solving format as before.

Figure 6: A Model of the Problem Solving Process

Any representation of a problem will be made up of several parts. They include:

1. A set of objects.

2. A set of operators that transform objects in the problem space into other objects.

3. An initial state.

4. A goal state.

In school problems, we are given all parts of the representation. We have the objects, operators, initial state and goal state. The learning objective is acquire a strategy for applying the operators. Even there, we are usually limited. Intentionally or not, most students learn that the way to solve the problem is to reproduce the "correct" solution methods in the book. It is small wonder that most people are not terribly creative at problem solving.

The choice of a representation can mean several things. First, it is the choice of problem. Our definition at the beginning of the section defined a problem as dissonance between the current state and the desired state. Finding a solution means reducing this dissonance. But, there may be more than one way to reduce this dissonance. The problem solver will not necessarily find the correct ways to reduce it. This is the problem finding process, and it is part of the process of choosing a good representation.

For example, suppose that a company is losing money. There may be many reasons for this. It could be:

1. A production problem.
   Production costs are too high; new equipment is needed.
   Inventory costs are too high; production schedules are bad.
   Shipping costs are too high; a new routing scheme is needed.

2. A marketing problem.
   Producing the wrong product for the market.
   Targeting the wrong market.
   Pricing the product incorrectly.

3. A financial problem.
   The company has cash flow problems.
   The capital structure needs revised.

4. A personnel problem.
   The company needs to be reorganized. Key workers are underpaid.

Once we have decided what the problem is, we have to choose a representation to express it. If the problem is a production problem where a new routing and warehouse structure is needed, perhaps a linear program would be a good representation. Maybe an integer vehicle routing algorithm would be more appropriate. The richer a repertoire of representations we have, the better we will do with the problem.

The choice of representation is a difficult problem. A good representation limits search without adding unnecessary constraints. It allows us to look at a problem in depth, discarding search paths that will be unproductive. Some of the specific problems with representations will be discussed in the next chapter.

3.1 PROBLEM SOLVING AS A PROCESS

The choice of a problem and a representation for the problem converts an ill-defined problem to a well-defined problem. With a representation in hand we can begin applying search strategies that transform an initial state into intermediate states and finally to our goal. If we are lucky, we may have an optimization problem. For optimization, we know that a solution exists that is better than or equal to all other possible solutions. If we are even luckier, we may have an algorithm that can discover this solution with a reasonable amount of effort.

More likely, however is the case where optimization is not possible. It may be possible, but we do not know how to do it or cannot do with reasonable effort. This is the case with many problems that generate computationally intractable integer programs (e.g. assembly line balancing problems). Then, we have to fall back on heuristics - that is rules of thumb. A heuristic generates good solutions with a reasonable amount of effort. It does not guarantee optimality. Consider chess as an example. It is possible to have a computer start with an initial chess position and generate end games. Then, all we have to do is pick the sequence of moves that guarantees us the best final position no matter what our opponent may do. This is the essential idea behind game theory and is called a "minimax" strategy.

This is not much help for solving real chess problems. It has been estimated that there are 10^{120} different endings to the game tree for chess. This is a big number, and we need to give it a little perspective. It has also been estimated that there are 10^{79} elementary particles in the universe. This means that there are 41 orders of magnitude more endgame situations in chess than there are elementary particles in the universe. Suppose then that every elementary particle in the universe were a computer grinding out chess solutions at the rate of one per nanosecond (much faster than any conceivable computer could do it). Then, it would take 10^{41} nanoseconds or about 3.2×10^{24} years to compute all chess endgames. Since the universe is about 2×10^{10} years old, this is roughly 160 trillion times the age of the universe. Computational problems of this magnitude are remote even if we could convince every elementary particle to be a computer.

Obviously, a strategy to limit search effort is needed. This is where heuristics come in. A heuristic is a rule to limit search in problem solving. In chess, there are many such rules. One example might be to protect your queen. This is the most powerful piece on the board, and you are in trouble if you lose it. On the other hand, blindly following this rule can cause one to overlook queen sacrifice strategies that could lead to a win.

There are many heuristics in general problem solving. Examples of search strategies include:

1. Trial and error - try all possible options without selection rules.

2. Depth first - search deeply along one search path.

3. Breadth first - search all the moves at one level before moving to the next level.

4. Segmentation - break a problem up into subproblems.

5. Hill climbing - make small moves in directions around your present position. Then move in the direction that yields the greatest improvement and start over.

6. Working backwards - assume you are at the solution and then reconstruct the moves you would have to have made to get there.

7. Analogy - compare this problem to an existing problem for which you already have a solution.

These problem solving methods can be regarded as a bag of tricks. No one problem solving method uses just a single heuristic. A good general problem solver would apply one or another where appropriate. As an example, consider chess again. The best approach might be to start with a breadth first search to identify likely candidate paths. A breadth first search is limited because of the many possibilities. After suitable candidates have been identified, the depth first techniques can be used. Analogy could be used to compare the current game situation with past games. Besides these general heuristics, special purpose heuristics could also be used.

The ideas behind general purpose heuristics are not difficult to understand. But, people seem to have trouble in applying the ideas. Research shows little transfer from the general techniques to specific problem domains. There may be many reasons for this. One may be insufficient practice in applying general as opposed to domain specific techniques.

4

PROBLEM DOMAINS AND THE ROLE OF MODELS

There are many problems when one tries to address problem solving in general. Problems present themselves in specific formats. Perhaps our education is responsible. Problems are always presented in the context of a course studying specific methods of solution. The focus is to learn the methods and get the answer in the book. Problem solving becomes a matter of acquiring specific techniques and replaying the appropriate script when the right problem comes along.

This type of education may be necessary for people to learn generally accepted methods of solving problems. But, it does not offer much guidance about what to do when faced with new kinds of problems. It is possible to go through formal education all the way to the doctoral level without ever considering how one actually solves problems. The process of solving problems has to be learned by example. The knowledge and methods picked up in courses forms a paradigm for a new generation of problem solvers to follow. There is seldom any attempt to generalize the methods learned in one area and transfer them to other areas.

A good example of this is calculus. Most of us remember the standard Freshman calculus sequence. The examples presented in the book exhibited a linear progression from initial assumptions to final solution. It was intimidating to find that one's own work toward a solution was seldom so clean or logical. It usually contained many false starts, backtracking and missed assumptions. If we were good at calculus, we could eventually approximate the solution methods in the book. If we were not, calculus rapidly became a traumatic experience. We felt that real mathematicians were those who could write the type of problem solving sequences illustrated in the text.

This is not necessarily true. If one were to go back to Newton's original work on the calculus, one would find that it was as full of false starts and strange assumptions as any other beginner's work. It is unlikely that even a professional mathematician today could read it and understand it. It was couched in terms acceptable to a limited number of seventeenth century mathematicians who were proficient in geometry. It is almost unreadable today. It was almost another century before the

Bernoulli brothers were able to put it into a form that could be widely applied.

This is especially noticeable in mathematics, but the same comments could be applied to any other branch of knowledge. Teaching was and is largely concerned with examples of solution techniques and transmission of knowledge. Very little of it focuses on the specific methods (if any) by which solutions are reached and new knowledge may be added.

4.1 EXAMPLES OF PROBLEMS

To illustrate some points about the structure of problems representations and problem domains let us consider some different problems. These are presented in no particular order.

1. Fill in the digits represented by the letters in the sum given below:

```
  SEND
+ MORE
 -----
 MONEY
```

   This is the type of cryptarithmetic problem that delights puzzle fans. Solving this one requires changing representation (substituting digits for the letters) using a trial and error process aided by a few heuristics (example - the letter M must represent 1). This example involves much backtracking and testing of assumptions.

2. Suppose that you were to meet a friend in New York City. You knew the date on which you were to meet but that was all. Your friend knew the same. You cannot communicate with each other to settle on a time and place. Choose a time and a place to meet your friend.

   It is obvious that this problem cannot have a "right" answer in the sense that a math problem can. But for large numbers of people (mostly those familiar with New York City), the problem may be solvable. The trick is to assume that the other person will choose an obvious place and time and then try to do the same yourself. It is an example of the way specialized knowledge is used in problem solving. The most common choice for New Yorkers is under the clock at Grand Central Station at noon. Non-natives do not do nearly so well on this one.

3. Give the next digit in the sequences:

1,2,3,4,5, ...

1,4,9,16,25, ...

1,2,3,5,7,11, ...

14,18,23,28,34,42,...

This problem is like many other problems in mathematics. The idea is to find the underlying pattern and then use induction to work things out. The trick is to recognize patterns, and test hypotheses about how those patterns are formed. The first sequence is simple counting, the second is the squares of the integers, and the third is the sequence of primes. All these nice logical sequences leave the problem solver unprepared for the fourth sequence. The next number in the sequence is 50, but the subject would be unlikely to get this without specialized knowledge. This is a sequence of subway stops on the IRT in Manhattan.

4. Solve the following for X:

X = 2*SQRT(2*SQRT(2*SQRT(...)))

This problem is an example of how representation can help. This problem looks almost impossible expressed in functional notation or in radical notation. If it is translated to exponential notation, it becomes trivial.

5. Suppose you had six toothpicks. Construct four equilateral triangles each of whose sides is one toothpick long out of the six toothpicks.

This problem offers an example of ways in which subjects can block themselves by adding constraints that are not there. To solve it, just construct a tetrahedron. That only requires six toothpicks and each face is an equilateral triangle. The problem for most people is that they add the unstated constraint that the figure must be two dimensional.

6. You have been challenged to a game of Number Scrabble. You and your opponent have nine tokens in a pile between you. The tokens are numbered 1 through 9. You take turns drawing tokens from the pile. The first person to have three tokens (drawn in any order) whose sum is 15 wins. Devise a strategy for this game.

The interesting thing about number scrabble is that you have already devised a strategy for playing it. Suppose you arranged the numbers like this:

6	1	8
7	5	3
2	9	4

This figure is called a "Magic Square". The magic is that the numbers in the rows, columns and diagonals all sum to 15. This is exactly the requirement for a win in Number Scrabble. With this change in representation, Number Scrabble should look familiar. It is an isomorph for Tic-Tac-Toe and the same strategies that work for one will work for the other.

7. Suppose you were General Eisenhower trying to decide how to choose a date for D-Day. How would you go about solving this problem?

   This is the classical unstructured, large, messy management problem. There is no particular method that will work. It is more a problem of defining the goal, breaking that definition down into subgoals, looking at constraints, modifying goals and so on. The paradigm developed by Newell and Simon works here too. It is just much more involved. The major problem (for General Eisenhower at least) was to structure the problem select the goals (by no means as clear then as now). He could let his staff work out the details while he monitored the progress.

One could go on with example problems forever. Sometimes this seems to be the approach of books on problem solving. The problems above are from a variety of areas. They are not necessarily "fair" in the sense that they follow well defined rules. They are not necessarily well structured. They do illustrate some good points about the problem solving process that reinforce the choice of a problem solving model made in Chapter 4.

First, there is the importance of choice of representation. This is shown in the square root problem, the six triangles problem, and the Number Scrabble problem. The wrong choice of representation can render even simple problems unsolvable. The right choice of representation can make a problem disappear. Deciding on what is the right or wrong representation is no easy matter. It seems clear that some representations dominate others (e.g. Arabic numerals as compared to Roman numerals). It is not clear how to set up criteria for comparing representations. One characteristic of gifted problem solvers is their ability to change representations. One example was Albert Einstein who used many unusual problem representations in deriving and explaining his theories.

A second point illustrated is the importance of knowledge in many problem solving situations. The problem about where to meet in New York, the last "complete the sequence" problem and Eisenhower's problem on D-Day all involve specialized knowledge. It would be convenient for education if specialized knowledge of real problem domains were not necessary, but this seems increasingly unlikely.

A final point illustrated by the last problem is the importance of problem finding. It was not obvious that the European invasion should take place in Normandy in the Spring of 1944. The Americans initially pushed for 1943. The Russians were pushing for a second front as early as possible. Churchill at times wanted to go for the "soft underbelly" of Europe by invading through Southern France or Sicily (perhaps he wanted to redeem the disaster at Gallipoli thirty years earlier). The initial problem here was to define the problem.

It seems that education concentrates mostly on the importance of knowledge. Choosing new representations or using problem finding skills is actively discouraged. If people are allowed to play with the representation of a problem, they might not learn the methods in the book. In general, this may not be bad. But it can discourage creativity in the gifted minority. The same is true of problem finding. All through the educational process, problems are given. Little attempt is made to break out and encourage students to find and define their own problem. If we are interested in teaching problem solving, these are issues that must be faced. By the graduate level, it may be too late to do this.

4.2 CLASSIFYING PROBLEM DOMAINS

Classifying problems into categories offers many possibilities for trouble. Any classification scheme is likely to be limited by the bias of the individual setting up the scheme. The present authors are no exception to this.

As a starter, we would propose classifying problems as either well defined or ill defined. A well defined problem can be defined as:

> A problem proposed to an information processing system is "well defined" if a test exists, performable by the system that will determine whether an object proposed as a solution is in fact a solution.[4]

This definition of a well defined problem fits most of the mathematical and logic problems commonly found in books. Many managerial problems, on the other hand would have to be classified as ill defined. The "information processing system" referred to in the quote is completely general. It could be either a man or a machine. For a problem to be well defined, we must have done the initial work of problem finding and selection of a representation. If not, no test can exist because we do not know what we are testing.

If no representation of the problem exists, then we have an ill defined problem. Our first task is to decide what the problem is. Then we can create a representation for it. This situation characterizes many of the management problems that a Naval officer (or any other manager) will face. In one sense, all problems could be considered well defined. If a problem is dissonance between the current state and a goal state, then any action that causes the dissonance to disappear is a solution.

As an example, consider a manager whose company is not profitable. He could view this problem in a variety of ways. Perhaps it is a marketing problem. The company has targeted the wrong market or is using the wrong advertising strategy. Maybe he could view it as a production problem. Production costs are out of control and need to be brought back in line. Perhaps it is a personnel problem. Poor employee morale is hurting productivity. Or perhaps it is not a problem at all. Maybe the manager views it as a startup phenomenon that will go away as the product line matures. The choice of representation and definition of the problem will determine what is done about it.

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[4] Allen Newell and Herbert Simon, *Human Problem Solving*, p. 73.

Once a problem has been defined and a representation chosen for it, then it becomes a well defined problem. Then, we have a series of steps (operators) that we can use for solving the problem, and a criterion for stopping our search. Most disciplines concentrate on this part of the problem solving process. This is not surprising. They are trying to teach problem solving within the framework of a discipline.

One way to represent problems would be as a task environment. In this approach, we partially follow Newell and Simon[5]. A task environment can be looked at in a variety of ways. They are:

1. A set representation of a problem.

   Given a set U, find a member of set U having specified properties (our goal).

2. A search representation of a problem.

   Given an initial state, a set of transformations and a goal state, move from the initial state to the goal state.

3. A design representation of a problem.

   Given a problem situation, define the problem and create a representation for it.

An example of the set problem might be to find the combination of a safe. The set of possible solutions is known but large and the problem is to search that space. An example of the second type of problem is the proof of a mathematical theorem. We begin with a set of initial conditions, we have a series of transformations, and we wish to arrive at our goal (the theorem) by applying these transformations. The implementation of the decision to invade Europe during World War II is an example of the last type of problem. So would the decision to set up a mass transit system for a city or region.

These three definitions of a task environment are not mutually exclusive. All three of them could be used in resolving a problem situation as might be the case in an engineering design problem. Most of our schooling revolves around the first two task environments. The real world is the last type.

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[5] Allen Newell and Herbert Simon, *Human Problem Solving*, pp. 73-77.

4.3 MODELS AS REPRESENTATIONS OF DOMAINS

When we find ourselves faced with a problem situation, we have to have some way of understanding it. For this, we typically use models of some kind. In this context, a model is a mental structure that can be used to test hypotheses and behavior of a real world system. A map would be an example of a model. It is an abstracted representation of real world features we are interested in. Maps will differ greatly in the features they show depending on the use we wish to make of the map. For instance, if we are hiking, our best choice is a contour map of the area. If we are flying a plane on instruments, we need a map showing names and frequencies of navigational aids and minimum safe altitudes on route. Terrain features are irrelevant in this kind of model.

A full discussion of modeling in problem solving would be philosophically involved, lengthy and beyond the scope of this report. Modeling is more of an art than a science. It is nothing more than the choice of representations for task environments. A good model should:

1. Display the state of the system before and after transformations.

2. Be capable of being manipulated.

3. Be capable of predicting system behavior.

4. Provide an adequate representation of all features of interest in the system.

An example of a model would be the use of Euclidean Geometry to represent limited portions of the surface of the earth. This fits points 1 through 3 for a good model. If we are only interested in limited surfaces, then it fits point 4 as well. Newtonian mechanics in physics is another model example. It fits points 1 and 2. For phenomena where relative velocities are low, it also does well on points 3 and 4. But, if we are talking about high relative velocities, it breaks down completely.

4.3.1 The Role of Assumptions in Modeling

Assumptions are constraints that allow us to bound a problem. The assumptions we make limit the solution search process. Reitman [1965] suggested that the process of problem solving is frequently the process of successively adding constraints to the problem state. Each constraint cuts away pieces of the solution set and reduces search.

Constraints may be externally imposed. All we need to do is have the wit to recognize them. Eisenhower's D-Day decision had many externally imposed constraints. The invasion had to take place in 1944 for political reasons. It had to be in the Spring to allow the Allies to take maximum advantage of good weather. There were only a few days in the Spring that allowed the right combination of tides for a landing. All these constraints helped bound the problem and reduce an unstructured design problem to a structured problem.

We have to be careful not to introduce unnecessary constraints in a problem. This is the case in the problem of the six toothpicks posed earlier. Subjects add a constraint that the solution be confined to two dimensions that makes the problem impossible to solve. This type of thinking gets in the way of innovative problem solving, but it is probably necessary. The addition of constraints makes the search process manageable and speeds up problem solving. At some point, it may be necessary to back up and remove constraints. This usually proves to be hard to do. The problem solvers we refer to as "geniuses" are usually the people who have this ability.

4.3.2 Limitations of Models

We must keep the limitations of models in mind. A model is not the real world. It is only an abstraction of that world. A model must be validated against an external reality. When we do this with most models, we find that it has a limited domain of applicability. There is nothing wrong with this. But, it does mean that we should sometimes go back and examine the constraints we have accepted by using the model.

It is important to realize that the choice of models is a choice. It is not something that must be accepted without question. Our representation of a problem offers both advantages and disadvantages. Students must realize this. Often, they have invested so much effort in learning a model that they are reluctant to abandon it. A problem solving course would have tc develop techniques to encourage students to move freely between different models of problems and to be creative in making up their own representations. This is one of the things that DeBono tries to do in his approaches to problem solving, and it is probably worth doing. The inability to see representations as arbitrary is probably one factor inhibiting transfer of learning in problem solving.

5

LEARNING TO APPLY GENERAL PROBLEM SOLVING TECHNIQUES

The study of problem solving has not made a large impact on education yet. This is not surprising. Education is a conservative field and is not quick to embrace fundamental changes even when they are of proven benefit. The so called New Math involved mathematical ideas that were about a century old when they were introduced. General problem solving is on nowhere near as sound a footing as the material in the New Math.

5.1 SURVEY OF TEACHING GENERAL PROBLEM SOLVING

There are few courses in general problem solving taught at the university level. We found documentation on two and have heard of others. The first course on which we have information is taught by John R. Hayes of the Department of Psychology at Carnegie-Mellon University and the other is taught by M. F. Rubenstein of the School of Engineering at UCLA. The course descriptions are given in Figure 7.

We have no firsthand knowledge of these courses, although we spoke to Hayes about the course at Carnegie. The course has been taught for several years now and has settled down. It is offered to entering students early in their career. Hayes has written a book[6] to support the course. The book is best described as an applied cognitive psychology text. It is divided into four sections. An outline of the topics is given in Figure 8. The first section deals with general search strategies. It tries to get the reader to see the general features of a problem instead of trying to reproduce a book solution. The second section deals with the classical cognitive psychology view of memory structure. It also offers strategies for structuring knowledge (mnemonics, time lines, etc.) that allow a student to acquire knowledge without trying to resort to simple cramming. The third section deals

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[6] John R. Hayes, *The Complete Problem Solver*, Franklin Institute Press, 1981.

Carnegie-Mellon University Department of Psychology

Psychology 85-113 - Psychology of Learning and Problem Solving

A course aimed at increasing students' learning and problem solving skills through understanding and applying topics in cognitive psychology. Topics covered will include representing problems, searching for solutions, making decisions, learning, use of technical reasoning. Considerable emphasis will be placed on learning and problem solving in the physical sciences.

UCLA School of Engineering

Engineering 11 - Patterns of Problem Solving

An introduction to patterns of reasoning in the process of problem solution and decision making. Exposure to concepts, theories and techniques in the analysis and synthesis of total systems in our complex technological civilization.

Figure 7: Course Descriptions in Problem Solving

with decision making. It discusses the structuring of decision problems and their impact on decisions. It also presents some statistical decision theory and cost-benefit analysis as examples of decision structuring tools. The last section is on creativity. It analyzes the sources of creativity and conditions affecting creativity. The book is written at a level that is appropriate for undergraduates.

During our visit to San Diego, we discussed the course with Hayes. He felt that it was working well after many years of experimentation and change. He also felt that the course was finally to the point where it was exportable to other institutions. Several different instructors had taught the course at Carnegie with reasonable success. There has been no formal validation of the course. Hayes said that he receives a gratifying amount of positive feedback from former students. He would like to perform a formal evaluation of his course, but has not had the time or resources to do so.

One important point that Hayes emphasized about this course was the need for practice in the problem solving techniques presented.

1. Problem Solving Theory and Practice

   a) Understanding Problems: The Process of Representation.

   b) Search

   c) Protocol Analysis

2. Memory and Knowledge Acquisition

   a) The Structure of Human Memory

   b) Using Memory Effectively

   c) Learning Strategies

3. Decision Making

   a) Getting the Facts Straight: Making Decisions in a Complex World.

   b) The Luck of the Draw: Dealing with Chance in Decision Making

   c) Cost-Benefit Analysis

4. Creativity and Invention

   a) Cognitive Processes in Creative Acts

   b) How Social Conditions Affect Creativity

Figure 8: Outline - The Complete Problem Solver

Without adequate practice, the whole thing is a meaningless exercise. This means that it would be necessary to choose a set of problems designed to emphasize the points presented in the course. The problems should probably be from domains of interest to the student. This means that "silly" problems (Tower of Hanoi, Missionaries and Cannibals, etc.) should probably be kept to a minimum. Some of these problems could be used to introduce the general nature of the problem solving process, but after that, examples that are relevant to the students' interests would be best.

Another factor that we feel is important is the teacher. The instructor of this course should be a first rate teacher with a good grasp of the principles and goals of the course. Hayes is an outstanding teacher (based on the author's personal experience). He knows the subject, he has a relaxed and supportive style, and he is able to draw on wide experience for relevant examples. These are essential points when one is trying to present material that is out of the ordinary. Some effort has to be made to sell the students on the usefulness of the course.

5.2 OTHER EDUCATIONAL RESEARCH IN GENERAL PROBLEM SOLVING

There is a small literature in educational research in the study of general problem solving. It does not seem to be an area that has attracted widespread interest when compared with the literature on more conventional subjects like mathematics or reading). One article by Post and Brennan [1976] dealt with an experiment in teaching geometry to two groups of tenth grade students.

The authors developed a test of problem solving ability and administered it as both a pretest and a posttest to two groups of tenth graders. One group had received instruction in the General Heuristic Problem Solving Procedure (presented in Figure 9) while the other did not. The reader should compare the model in Figure 9 with that of Polya's in Figure 1. The two are similar, although Post and Brennan do not cite Polya. The two groups did not show any significant difference in problem solving ability. The authors offer a detailed discussion of the statistical methodology they used. This discussion would be appropriate for a beginning experimental methods course. Unfortunately, they tell us nothing about how the problem solving methodology was taught. Were students merely exposed to it? Did they get substantial practice with it? These are questions left unanswered. The conclusions in the article are too strong to be justified by the material presented.

Raaheim and Kaufmann [1974] tested 73 secondary school students using tests of the subjects' ability to manipulate their environment. In one test, the subjects were asked to tell how to save a kitten stranded at the top of a tree. The lowest branch on the tree was too high to reach. The tools that they had available were a strong drill, a hammer, a pair of pliers and a plane. The "best" solution involved drilling holes in the tree trunk and then using the hammer, pliers and even the drill as "steps" to climb the tree. There were other tests in a similar vein. They seemed to test the subjects' ability to overcome functional fixity in solving problems.

I. Recognition, Clarification and Understanding of the Problem.
   1. Read the problem carefully.
   2. Look up any words you do not understand.
   3. What is the unknown? What are the data? What is the condition? What is given?
   4. State the problem in your own words.
   5. Break the problem into parts.
   6. Draw a diagram to aid in clarification.
   7. Accept or reject the specific problem tools as a problem for yourself.

II. Plan of Attack - Analysis
   1. Gather data (facts, rules, relationships) which are necessary for solution.
   2. Recall missing data, select relevant data from the problem statement, and generate new data if necessary.
   3. Eliminate irrelevant data.
   4. Decide on needed approach activities by noting obstacles to the solution of the problem.

III. Productive Phase
   1. Find the connection between the data and the unknown. You may have to consider auxiliary problems if an immediate connection cannot be found. Do you know a related problem?
   2. Generate a hypothesis or a number of alternative hypotheses (possible solutions of the problem).
   3. Order your data in preparation for hypothesis testing.
   4. Reject initial hypotheses that do not satisfy the conditions of the problem.
   5. Select a remaining hypothesis for testing.
   6. Construct an algorithm or develop a heuristic for the manipulation of data as an instrument for possible verification of a hypothesis.

IV. Validating Phase - Checking - Proving
   1. Accept or reject the hypothesis by verifying or not verifying that it meets the conditions of the task.
   2. Look back. Can you check the result? Can you check the argument? Can you derive the result differently? Can you use the result or the method for some other problem?
   3. If you have rejected your hypothesis, select a remaining one for testing.

Figure 9: General Heuristic Problem Solving Procedure - Post

Success on their tests correlated highly with IQ. Girls were significantly poorer problem solvers than boys. The authors attributed this to their unfamiliarity with the tools posed in the problems. A possible alternate explanation might be that girls are more strongly socialized to be "good". This would tend to cause them to ignore the rule breaking required in these problems. The authors conclude that general problem solving ability exists and is highly correlated with conventional measures of intelligence.

The paper by Reif and Heller [1982] is a prescriptive piece. They lay out a teaching methodology for physics based on the general problem findings in cognitive psychology. They outline a strategy for structuring knowledge and acquiring knowledge in physics. They present a detailed program for physics instruction. There is no empirical validation, but they do try to tie the points stated in their recommendations into previous empirical work.

A series of papers by Feldhusen et. al. [1972, 1975, 1979, and 1980], Houtz et. al. [1973] and Speedie et. al. [1973] covers research done in general problem solving in education at Purdue University. The work developed a measure of problem solving ability appropriate for elementary school children from different socioeconomic and cultural backgrounds. Because of the age of the students involved, this work is not relevant to this report. One interesting thing about this series of papers. They point up the isolation of the education literature from other research in problem solving. It is not until the 1979 paper in the series that any work by Simon is mentioned. Most of the references are to educational journals. The papers themselves are heavy with educational jargon that helps hide their lack of useful content.

A paper by Thorsen [1977] discusses the use of simulation to teach problem solving approaches at Denison University. The paper itself is a short survey of the problem solving literature followed by arguments justifying the use of simulation for the teaching of problem solving. The article has little to say about the teaching of problem solving. It does not even tell us whether the experiment was successful or what might constitute success or failure.

A paper by Baird [1983] offers an interesting summary of the problem solving research in education. Baird's report is similar to ours in that he is surveying the literature to see what has been done in problem solving and what benefits may result from teaching problem solving. He concludes that the benefits from teaching generic problem solving are difficult to prove. He believes that general problem solving techniques are probably most effective when they are integrated into domain specific courses.

A last paper is that by Ruth Pitt [1983]. It is a comprehensive literature survey of the psychological literature on the development of general problem solving schema. The work concludes that the development of a GPS schema takes place between adolescence and early adulthood. She studied two groups of students, one group of tenth graders and one group of college students. She found that the tenth graders had limited ability to define problems and generate hypotheses. They did not seem to have a rich set of problem representations or methods for dealing with problems. The college students were much better. Their abilities approached that of professors on most measures. The findings here are preliminary, but there are some interesting implications. Pitt suggests that the time to teach general problem solving techniques is in early adolescence when such concepts are being formed. More mature students are likely to respond better to domain specific techniques. For better or worse, their skills may already be formed.

If these papers are indicative of the general level of interest in education in teaching general problem solving, then the level of interest cannot be very high. It would seem that the primary influence of the general problem solving work has been to stimulate new approaches to the teaching of conventional disciplines as in the Reif and Heller article. There is little work involving the teaching or study of general problem solving ability. It may be that the concept is too hard to define and that it is safer to stay with conventional disciplines. It may also be that the best approach to general problem solving techniques is to integrate them in conventional areas to improve retention and comprehension.

5.3 EXPLORATION - A STUDY OF PROBLEM SOLVING

An interesting literature studying problem solving is growing in the intersection between computer science, human factors and psychology. This is the study of exploration and exploratory environments. This literature is represented in the papers by Anzai and Simon [1979], Carroll, et. al. [1982, 1982a, 1983, 1983a, 1984, and 1984a], Darlington, et. al. [1983], Lewis, et. al. [1982], Malone [1981, 1981a, 1981b, 1981c, and 1982), Schrager and Klahr [1983] and Winston [1980]. This literature looks at the way people learn about an environment without formal instruction. They must take their clues from the environment, form hypotheses and act on the basis of these hypotheses.

This study is of interest to cognitive psychologists because it provides a way to study human problem solving behavior in a controllable environment. It is of potentially greater payoff to the computer industry. The quality of the man-machine interface can be crucial to the success of a piece of software. In microcomputing, some programs are popular partly because of their ease of use (LOTUS 1-2-3 is a good example). Other programs that may be equally powerful but unappealing to use become commercial failures.

Carroll [1982a] compares learning to use a word processor with the fantasy game "Adventure". Both are computer programs. The Adventure program is intentionally confusing, but it draws users into the world it creates. In Carroll's comparison, many word processors offer the same kind of confusion as Adventure without offering a balancing incentive to push past the confusion and learn the system. Carroll's classification of problems faced by these computer users is given in Figure 10.

Disorientation	The user/player doesn't know what to do in the system environment.
Illusiveness	What the user/player wants to do is deflected toward other, perhaps undesired, goals.
Emptiness	The screen is effectively vacant of hints as to what to do or what went wrong.
Mystery Messages	The system provides feedback that is useless and/or misleading.
Slipperiness	Doing the "same thing" in different situations has unexpectedly different consequences.
Side effects	Taking an action has consequences that are unintended and invisible but cause trouble later.
Paradox	The system tells the learner/player to do something that is clearly inappropriate.
Laissez-faire	The system provides no support or guidance for overall goals (e.g. "winning" "typing a letter")

Figure 10: Typical Problems Faced by Users - Carroll[1982a]

The problems noted by Carroll can be formidable obstacles in learning to use a computer system. Some people regard them as so intimidating that they are never able to master the machine. Others regard them as a challenge and even become compulsive about responding to it. Carroll offers a series of suggestions for system design to reduce the problems noted in Figure 10. These suggestions are given in Figure 11. Carroll regards his work as preliminary. These results were published in the *IEEE Computer*, and seemed generally interested in stimulating thought on software design issues.

Responsiveness	When you do something, you get some feedback (at least informational).
Benchmarks	You can tell where you are within a given episode or session. You have the means for assessing achievement and development of skill.
Acceptable uncertainty	Being less than fully confident of your understanding and expertise is OK.
Safe Conduct	You cannot do anything too wrong.
Learning by doing	You do so that you can learn to do; you design a plan; you do not merely follow a recipe.
Opportunity	Most of the things you learn to do work everywhere. You can reason out how to do many other things.
Taking charge	If progress stagnates, something new is suggested or happens spontaneously.
Control	You are in control or at least have the illusion of being in control.

Figure 11: Exploratory Environment Characteristics - Carroll[1982a]

Malone [1981] is studying the same kind of issues as Carroll. His work also focuses on the relationship between computer games and more conventional computer programs. He is interested in what makes games so intriguing and whether these features of the game interface could be transferred to other programs. He ran subjects through a series of learning game experiments and tried to abstract features of the game that worked best. From this, he developed a set of heuristics for designing enjoyable interfaces. These are given in Figure 12.

This work with exploratory environments is trying to find out how people solve problems in a system where there are few formal clues to proper behavior. This has always been a feature of computer systems. The manual never tells you everything there is to know about a system. It simply cannot. The combinatorics render that impossible. It has always been true that some people are inherently better explorers of this computer environment than others. But until recently, there has been no research into why this might be so. Microcomputers and video games have made this a more pressing question. The video games show that exploration of complex environments is feasible and even a reasonable thing to do. There are few manuals to video games. The widespread use of micros even by non-technical individuals makes a better understanding of exploration necessary.

The work on exploration in the references is interested primarily in the interface design question. But, there is a flip side to this that is of interest in this research. How can we teach people to be better explorers? Is this a teachable skill? This is the same question (applied to a narrower domain) that motivates this whole report. As computers become more pervasive, this is a question that deserves research.

I. Challenge

A. Goal. Is there a clear goal in the activity? Does the interface provide performance feedback about how close the user is to achieving his goal?

B. Uncertain outcome. Is the outcome of reaching the goal uncertain?

1. Does the activity have a variable difficulty level? For example, does the interface have successive layers of complexity?

2. Does the activity have multiple level goals? For example, does the interface include scorekeeping?

II. Fantasy

A. Does the interface embody emotionally appealing fantasies?

B. Does the interface embody metaphors with physical or other systems that the user already understands?

III. Curiosity

A. Does the activity provide an optimal level of informational complexity?

1. Does the interface use audio and visual effects: (a) as decoration, (b) to enhance fantasy and (c) as a representation system?

2. Does the interface use randomness in a way that adds variety without making tools unreliable?

3. Does the interface use humor appropriately?

B. Does the interface capitalize on the users' desire to have "well-formed" knowledge structures? Does it introduce new information when users see that their existing knowledge is (1) incomplete, (2) inconsistent or (3) unparsimonious?

Figure 12: Interface Design Heuristics - Malone [1981]

5.4 HUMANS AS PROBLEM SOLVERS

The most comprehensive theory of human problem solving behavior is that of Newell and Simon. They worked this theory out over many years. The most complete explanation of the theory and its justification and sources is found in their book *Human Problem Solving*. Theirs is an information processing view of the psychology of problem solving. The model is computer-like in its assumptions about humans.

The basic components of the model are:

1. Receptors and Effectors

2. Processor

3. Short Term Memory (STM)

4. Long Term Memory (LTM)

5. External Memory

Data about the environment is gathered by the receptors. It is held in STM and is immediately available for processing. Experimental evidence [Miller, 1956] indicates that the STM is limited in its capacity. The STM corresponds to temporary buffers in computing. More recent psychological research has also suggested the existence of an Intermediate Term Memory (ITM). This memory controls our daily lives holding our memory of things like our daily schedule, appointments, and so on. This would correspond to the core memory in a computer system if it exists. Beyond this, there is the long term memory. The LTM presumably is large enough to store the memories of a lifetime. In a computer system, the analogy is the on-line mass storage. The EM is whatever memory aids we choose to use (e.g. paper notes). The computer analogy might be off-line archival storage.

The processor corresponds to the CPU plus program in a computer. It seems to operate as a serial processor although this is hard to define exactly. It is obvious that there is a limited degree of parallelism in neurological processes, but the basic control seems to be serial. Processing seems to have an internal clock time of about 40 milliseconds between elementary operations (about 250 operations per second). The comparable rate for computers is between 10,000 and 100,000 times faster. The basic operation is a simple store and compare. The decision making process seems to behave like a production rule system. Interestingly enough, this production rule approach is the same one used in the "Fifth Generation" for implementing expert systems in computers [Clocksin and Mellish, 1981].

The model is mostly a theoretical construct based on a synthesis of research done by many psychologists. The approach used in testing many of their theories included computer simulation. It is possible to implement this model on a computer and let the computer help work out the implications of the theory. This work has had at least as much impact on computer science as it has on psychology.

The educational implications of the Newell-Simon model are less clear. It is a descriptive not a normative model. The obvious parts of the model to focus on in improving general problem solving ability are the Processor and LTM components. The difference between good problem solvers and poor ones is probably in the processing rules they use for information. If good processing rules can be discovered and taught then there may be real utility to teaching general problem solving. The LTM component could be improved by teaching improved recall and structuring of knowledge. All this is easier to do with machines than people. Perhaps this is why this theory has had more impact on computer science than on education.

6

DIRECTIONS FOR FUTURE RESEARCH AND DEVELOPMENT

The usefulness of teaching general problem solving is not fully established. The literature surveyed in this research shows some interest and activity in the area. Compared to thirty years ago, there has been a sizeable increase in interest. This increase was initially started by work in artificial intelligence and cognitive psychology in the 1950's. In the 1970's and 1980's, the influence began to be felt in education. In addition, the growth of interest in artificial intelligence and expert systems is likely to mean increasing stress on the study of problem solving.

The value of teaching general problem solving is likely to remain unproved for some time. It is unclear whether the subject can be taught successfully. All during our education, we learn to solve specific problems, not general ones. Our education forces us to think of domain specific problem solving. There may be transfer of problem solving skills from one area to another (this is the normal justification for teaching liberal arts), but this remains unproved as well. The literature in this area is too sketchy to be able to give a definitive answer.

6.1 PROBABABLE USEFULNESS OF TEACHING PROBLEM SOLVING

Much of the discussion and activity in the teaching of general problem solving would appear to be based only on the hope that it can help. Some research is openly critical of the usefulness of general problem solving instruction [Post and Brennan, 1976]. Other work is more optimistic [Reif and Heller, 1982; Thorson, 1977] but it is still largely unvalidated. During our conversations with Hayes in San Diego, he stated that there is little or no validation of the work he and others have done. What validation exists is casual, based on fragmentary feedback from former students. He would like to conduct formal validation of the course, but has not had the time or resources so far to do this.

It would be useful for Naval officers to have some exposure to the theory of problem solving if only because this area is a basis for the so called "expert systems" that are becoming become increasingly important. A background in the techniques used in general problem solving and artificial intelligence would be helpful in understanding these systems. This could be useful even if the student's own problem solving ability were not substantially improved.

6.2 TEACHING PROBLEM SOLVING

The inescapable fact remains that problem solving is wedded to a choice of domain. It is difficult for people to get from their domain specific knowledge to any kind of overview of the problem solving process. It has only been comparatively recently that people did research on the subject of problem solving in general apart from a specific domain.

Much of the material that is supposed to be "general" in fact begins to seem domain specific when you look at it closely. It usually includes such things as thinly disguised logical puzzle or mathematical problems. Hayes' book has many problems of this type. This approach is probably useful for well defined problem. The well defined problems may be more typical of problems like computer program debugging, electrical or mechanical troubleshooting, etc. These problems are ones in which we already have a problem and a representation. The rules for manipulating the representation are well known. For this kind of problem, teaching general search heuristics may well be beneficial. Good problem solvers in these domains already know these heuristics, but teaching the heuristics to beginners might help shorten the learning time required to achieve competence.

These search heuristics are less likely to be useful where the problem is ill-defined. In this type of problem, the first phase of problem solving is a design component. It is necessary to decide what the problem is and to select or create a representation for it. It would probably be more useful to teach techniques for selecting, defining and representing problems. The approaches used by DeBono and others might be useful here. The elaborate search heuristics may be less useful for ill-defined problems. Many management problems would best be characterized as ill-defined.

6.3 VALIDATING RESULTS

For any work in teaching general problem solving, a major problem is going to be validation of the results. We were not able to find any generally accepted measures of problem solving ability applicable to a population of college educated adults. The work we came across was geared toward grade and high school students. This work also tends to be oriented toward well-defined rather than ill-defined problems. These problems are easier to measure and easier to achieve agreement on standards for success.

If one wishes to teach generic problem solving as a basic subject at this level, it will be necessary to develop measures of problem solving ability. This will not be easy to do. It may well prove impossible to find measures that do not discriminate in favor of cultural or domain specific skills. It has proven difficult to create measures of general intelligence. It is likely to be even more difficult to create widely acceptable measures of general problem solving ability.

6.4 FUTURE WORK IN TEACHING GENERAL PROBLEM SOLVING

General problem solving may be too nebulous a term for the things we have been discussing here. A better term might be "learning strategies" since this is the focus of work like Hayes and Rubenstein. It seems that future work in this area should proceed slowly and deliberately. It should involve both curriculum development and basic research. The curriculum development could provide a course to serve as a vehicle for testing theories turned up in research. The available literature does not support the idea that general problem solving is a subject suitable for inclusion in standard training sequences or core courses.

One point that Hayes emphasized strongly was that it was not enough to lay out principles of general problem solving and expect the students to pick them up. Good examples and practice are required. This is one reason that it is likely to be difficult to set up a "general" problem solving course. Most course material is oriented to demonstrating the techniques involved in a particular discipline. There is usually little effort made to illustrate general principles or give help in applying them. New course material would have to be developed.

A course in general problem solving would have to be carefully designed. Adult students are more likely to respond to domain specific material. This would make them feel that the course was relevant to their interests and probably make them more enthusiastic about learning the material.

6.5 DIRECTIONS FOR FUTURE RESEARCH

There is a need for both theoretical and applied research in problem solving. Topics of interest include:

1. Design of measures of problem solving skills. Most measures in use currently are aimed at younger students. They are also aimed at well-defined problems and domain specific skills. Some broader measures of problem solving ability are required.

2. Design of course modules in problem solving covering both domain specific and general skills. The needs of the Navy involve both education and training. Practice with courses appropriate to both areas is required.

3. Experiments where the usefulness of teaching problem solving skills is tested. Once the courses and measures of ability are in place, they must be debugged.

4. Studies of computers and human problem solving. These should focus on the computer as a problem environment and ways in which the computer can aid human problem solving. The pervasiveness of computers in our environment makes it essential that we develop a better understanding of the ways in which people use them.

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